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13. ABSTRACT (*Maximum 200 words*)

This report contains a brief summary of accomplishments achieved under ARO sponsored research into the formulation and numerical analysis of discontinuity problems in MIC's that are printed on anisotropic substrates. Complete listing of research publications is provided which detail advances made in three technical areas during the course of the research project. Specifically, the cited references point to the reports on a block-transfer-matrix method for MIC's on multi-layered anisotropic substrates, new method of lines formulation for materials with dielectric and magnetic tensor properties and a new enhanced spatial network approach to numerical analysis of MIC discontinuities in the time domain.

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# MODELING OF MILLIMETER-WAVE MICROSTRUCTURE DISCONTINUITIES ON ANISOTROPIC SUBSTRATES

FINAL PROGRESS REPORT

Benjamin Beker

COVERING PERIOD:
1 September 1992 - 31 August 1996

U.S. ARMY RESEARCH OFFICE

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STATEMENT OF THE PROBLEM STUDIED

Improving the analytical and numerical prediction methods for electromagnetic characteristics of microstrip discontinuities, which are common in microwave and millimeter wave integrated circuits (or MIC's), represents an active area of research. This is especially true in determining the high-frequency electrical response of MIC discontinuities printed on anisotropic substrates. The state of knowledge in the area of discontinuity analysis for open MIC's with anistropic substrates was very limited prior to this research. In spite of this, such substrate materials were still commonly used in many practical MIC's. The lack of prior understanding of fundamental principles governing the physics of guided wave propagation through both dielectrically and magnetically anisotropic media motivated the research carried out under the sponsorship of this grant.

SUMMARY OF MOST IMPORTANT RESULTS:

During the course of the research, the most significant progress in advancing the state of knowledge was made in three technical areas. First, a new block-transfer-matrix method was developed to efficiently exploit Green's function formulation in propagation and discontinuity problems. This is especially convenient for MIC's which are printed on anisotropic substrates. The added complexity due to the substrate material being both dielectrically and magnetically anisotropic, requires very efficient ways to enforce the boundary conditions between the layers, when deriving the spectral domain Green's function for the multi-layered structure. Such problems do not appear in the analysis of isotropic substrates, since for such materials there is no coupling between components of electric and magetic fields that are tangential to the interface. The application of the new block-transfer-matrix technique allowed for the analysis of both uniform transmission lines and patch resonator arrays printed on anisotropic substrates which would, otherwise, be impractical, if not impossible, with the use of existing methods.

The second significant technical contribution was made in formulating and applying the Method of Lines (MoL) to the numerical analysis of MIC discontinuities which use anisotropic substrates. Prior to this research, application of MoL was restricted to very simple uniaxial anisotropic materials. The research efforts carried under the support of

this grant have extended the use of MoL to biaxial substrates. In addition, the new formulation also permits analysis of substrate materials which are characterized by both their permittivity and permeability tensors simultaneously. The modified MoL approach was applied along with the transverse resonance technique to study dispersion properties of microstrip step discontinuities.

Finally, in addition to advancing the frequency domain techniques described above toward the analysis of anisotropic substrates, time domain methods for the numerical modeling of MIC discontinuities we considered as well. The spatial network method (SNM) was modified with absorbing boundary conditions (ABC's) to analyze open MIC problems. These initial efforts lead to subsequent advances in SNM, improving the speed of the algorithm by a factor of 10 and reducing the computer storage requirements by a factor of 6! These results represent a very significant advance to MIC discontinuity modeling techniques in the time domain. They will be explored further for simulations of arbitrary 3-D MIC discontinuities.

## SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

1. Yinchao Chen, awarded Ph. D. degree
2. Deepak Jatkar, awarded Ph. D. degree
3. Dragos Bica, will be awarded Ph. D. degree in April 1997.

## LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS PERIOD, INCLUDING JOURNAL REFERENCES:

1. Y. Chen and B. Beker, "An efficient analysis of anisotropic multiconductor-multilayered MICs using SDA and Block-Transfer method," *Microwave Opt. Technol. Lett.*, vol. 6, no. 8, pp. 486-490, June 1993.

2. Y. Chen and B. Beker, "Analysis of microstrip lines with anisotropic substrates using the MoL," *Proc. 9th COMPUMAG Conf.*, pp. 348-349, Miami, FL, Oct. 1993.

3. Y. Chen and B. Beker, "Analysis of coupled microstrip patch resonators printed on anisotropic substrates," *IEEE MTT Int. Symp. Digest*, vol. 1, pp. 353-356, San Diego, CA, May 1994.

4. Y. Chen and B. Beker, "The methof of lines analysis of striplines with double layered or suspended bianisotropic biaxial substrates," *IEEE Trans. Microwave Theory Tech.*, vol. 42, no. 5, pp. 917-920, May 1994.

5. Y. Chen and B. Beker, "Application of MoL to shielded microstrip lines with bi-anisotropic substrates and cover layers," *IEEE Trans. Magnetics*, vol. 30, no. 5, part II, pp. 3212-3215, Sept. 1994.

6. Y. Chen and B. Beker, "Study of microstrip step discontinuities on bianisotropic substrates using the method of lines and transverse resonance technique," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-42, no. 10, pp. 1945-1950, Oct. 1994.

7. Y. Chen and B. Beker, "Analysis of coupled microstrip patch resonators printed on anisotropic substrates," *IEEE Trans. Microwave Theory Tech.*, *IEEE Trans. Microwave Theory Tech.*, vol. MTT-43, no. 2, pp. 460-463, Feb. 1995.

8. Y. Chen and B. Beker, "Analysis of complementary slot and strip resonators printed on anisotropic substrates using two-dimensional spectral domain method," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-43, no. 7, pp. 1605-1607, July 1995.

9. D. Bica and B. Beker, "Analysis of microstrip discontinuities using the spatial network method with absorbing boundary conditions," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-44, no. 7, pp. 1157-1161, July 1996.

10. D. Bica and B. Beker, "Analysis of microstrip discontinuities using the enhanced spatial network method," revised and resubmitted to *IEEE Trans. Microwave Theory Tech.*, Oct. 1996.